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Annual Report and
Proposal for Continuation of
NASA CONTRACT NCC3-414
**LOBED MIXER OPTIMIZATION FOR
ADVANCED EJECTOR GEOMETRIES**

submitted to:
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INVESTIGATOR:**

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AMOUNT:

~~\$1,500,000~~

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LOBED MIXER OPTIMIZATION FOR ADVANCED EJECTOR GEOMETRIES

1.0 Summary

This is a proposal for continuation of NASA Contract NCC3-414, "Lobed Mixer Optimization for Advanced Ejector Geometries". The overall objectives are: *i*) to pursue analytical, computational, and experimental studies that enhance basic understanding of forced mixing phenomena relevant to supersonic jet noise reduction, and *ii*) to integrate this enhanced understanding (analytical, computational, and empirical) into a design-oriented model of a mixer-ejector noise suppression system. The work is focused on ejector geometries and flow conditions typical of those being investigated in the NASA High Speed Research Program (HSRP). The research will be carried out in collaboration with the NASA HSRP Nozzle Integrated Technology Development (ITD) Team, and will both contribute to, and benefit from, the results of other HSRP research.

The noise suppressor system model that is being developed under this grant is distinct from analytical tools developed by industry because it directly links details of lobe geometry to mixer-ejector performance. In addition, the model provides a "technology road map" to define gaps in the current understanding of various phenomena related to mixer-ejector design and to help prioritize research areas. This report describes research completed in the past year, as well as work proposed for the following year.

2.0 Background and Motivation

A primary source of the noise produced by jet aircraft during takeoff and landing is the turbulent velocity fluctuations arising from the interaction of the engine exhaust jet with the freestream. The acoustic power generated from this mechanism is proportional to the eighth power of the jet velocity at subsonic Mach numbers and the third power of the jet velocity at sufficiently high supersonic Mach numbers. The substantial decreases in noise produced by commercial aircraft have been achieved largely through reducing this velocity. For high bypass ratio engines typical of subsonic transport aircraft the velocity decrease is achieved through mixing of the inner core flow with the bypass air, but there are prohibitive drag penalties associated with this type of solution at supersonic speed. As a result, efforts are underway to develop advanced mixer-ejector noise suppressors which entrain freestream flow that mixes with the exhaust jet and reduces its velocity within these ejectors. Lobed mixers are typically employed to enhance mixing through introduction of streamwise vorticity. The proposed studies are aimed at the technology of these

lobed mixers and its use in the design of noise suppressors.

2.1 HSR Program Requirements

The current status of the nozzle development effort being pursued under the NASA High Speed Research Program is that simultaneous attainment of thrust coefficient, noise suppression, and weight goals has not been achieved. Further, due to the complexity of the multi-parameter nozzle design problem, at present there is an insufficient understanding of the achievable performance limits and high leverage design parameters necessary to assure that HSR Program goals will be met in the near future.

Several items have been identified by the HSRP Nozzle ITD Team as critical in moving the nozzle design process forward towards the program goals. One of these items is a physically-based, systems-level noise suppressor model/design tool. Through comparison with HSR Program data the model will allow determination of achievable performance limits, will provide a "technology road map" to define gaps in the current understanding of various phenomena related to mixer-ejector design, and will help prioritize other HSRP research.

Critical components of an effective noise suppressor system model are:

- 1) The fluid mechanics and acoustics must be viewed within the context of a mixer-ejector. This is provided through use of the current compound flow analysis (CFA) model.
- 2) The system model must contain high-fidelity mixing and loss sub-models which connect the details of the fluid dynamic processes to duct and lobe geometry and flow conditions.
- 3) The system model must contain simplified acoustic sub-models which connect details of the fluid dynamic processes to relevant noise metrics
- 4) All sub-models incorporated into the system model must be simple enough to allow efficient use of the tool for parameterization, sensitivity studies, and optimization analysis. Determining what to exclude from the system-level model is as important as determining what to include.
- 5) The model must not be static, but must evolve through a continuing validation process fed by HSR Program data, numerical simulations, and enhanced understanding brought about by basic research into high leverage underlying physical phenomena.

The development of this noise suppressor system model is the focus of the current research effort.

2.2 Other MIT Noise Suppressor Research

The noise suppressor research currently being carried out in the MIT Aero-Environmental Research Laboratory falls into two general areas: 1) applied research, devoted to the development of a physically-based noise suppressor design tool, and 2) basic research, directed at providing an understanding of the underlying physical phenomena. Both components are required for an effective research program; design tools cannot be developed without understanding the physical phenomena; the important physical phenomena cannot be identified without a design tool. The development of a system design tool is the subject of this grant effort. The second area of research is briefly reviewed below since it both contributes to and benefits from the design tool development effort. This area was previously supported by a NASA Langley grant and in the future will be funded by the NASA Lewis HSRP through a subcontract with Pratt and Whitney.

2.2.1 Compressible Mixing Experiments and Analysis

The objective of this research is to provide a detailed understanding of the mixing process downstream of lobed mixers in flow regimes of interest for HSCT noise suppressor applications. Specifically we are investigating the influence of streamwise vorticity on mixing rates in compressible mixing environments. We are conducting first-of-a-kind shear layer experiments at United Technologies Research Center in which we *independently* vary the magnitude of the shed streamwise circulation, the convective Mach number, and the stream-to-stream velocity ratio. Diagnostics for the tests include planar Mie scattering imaging from ethanol condensate, Schlieren photographs, mixing duct wall static pressure measurements, Pitot probe flow surveys, surface oil flow visualization, and acoustic measurements with flush-mounted wall microphones.

Experiments such as these are critical for the development and validation of models which will be input into the noise suppressor system model. An example of a successful model which grew out of this effort is a mixing model based on vortex dynamics which can be used to rapidly (5 to 20 minutes) compute details of the mixing downstream of complicated lobe geometries. Because of the high-fidelity of the mixing model (the geometry of the mixing interface is computed), it may also provide a basis for effective simplified acoustic models of internally and externally generated noise.

2.2.2 Acoustic Experiments and Analysis

The objective of this research is to elucidate the links between acoustics and flow structure in strongly augmented mixing flows typical of jet noise suppressors. This is critical for providing a basis for understanding noise generation internal to the ejector, for designing acoustic treatment,

and for developing and validating simplified models for acoustic radiation which may be incorporated into the mixer-ejector system model. The issues we hope to address include: defining the relative merits of mixing with streamwise vorticity versus transverse Kelvin-Helmholtz structures, and assessing the impacts on both mixing and acoustics of lobe geometry changes such as stagger and tabs. As a result of several years of basic research we have developed a detailed understanding (and an ability to model) the mixing process; the critical next step is to make the connection to acoustic radiation. Currently no simplified acoustic model exists for integration into the noise suppressor system model. A unique shock tube facility we have designed will serve as an important tool for these studies.

When completed, the twelve inch diameter acoustic shock tube will be the only facility of its kind in the world. A shock wave will be used to generate a reservoir of high pressure and high temperature air for use as a primary flow source for various noise suppressor nozzle configurations. The facility will produce fluid mechanical and acoustic data which matches that obtained in steady-state facilities. One of the advantages of this approach is that the total temperature and pressure profiles at the nozzle inlet are uniform as a result of shock heating. Also, with modern measurement techniques, the short run times (~20 ms) can be turned to a benefit: relatively inexpensive stereo-lithography models can be tested at realistic flow conditions. In addition to these technical advantages, the size of the shock tube facility makes it ideally suited to operation in a research university environment. The facility will provide the HSR Program with an economical, rapid-prototyping and testing capability which does not currently exist.

Both the compressible mixing research described in Section 2.2.1 and the jet noise research described above, will provide data for the continued validation and development of the noise suppressor system model. This model, which is the subject of the current grant effort, is described below.

3.0 Review of Progress on the Noise Suppressor System Model

To develop a physically-based noise suppressor system design tool, analytical models of lobed mixer performance are being formulated and integrated with numerical and empirical information. The foundation for the system model is a compound compressible flow code written and developed by MIT. The most significant difference between this model and those which exist in industry is that the mixing in the ejector duct will be directly related to details of the mixer lobe geometry through models that we have developed. Parametric variations of lobe geometry (lobe aspect ratio, penetration, flow leaving angle, tabs, etc.) can thus be investigated at much lower cost than with three-dimensional computational simulations or experimental testing. The high-fidelity of the mixing model (the evolution of the mixing interface is captured) may also allow the development of more effective, simplified, internal and external acoustic models.

The project has been divided into five task areas:

- 1) Development of a simulation framework
- 2) Evaluation and refinement of models by comparisons to experimental data
- 3) Development of models linking simulation to desired figures of merit
- 4) Embedding the simulation into optimization routine
- 5) Performance of optimization studies

At this time, the simulation framework has been developed (Task 1) and aerodynamic models have been linked to it. The evaluation and refinement of these models is ongoing (Task 2). These topics are reviewed in more detail below. Tasks 3-5 will be the subject of the future work described in Section 4.0.

3.1 Simulation Framework: Compound Flow Analysis (CFA) Code

The framework for the simulations is a compound flow analysis (CFA) approach. Compound flow analysis models the ejector using a two stream differential control volume. The two streams interact at their common interface through the exchange of momentum (through pressure and shear forces) and the exchange of energy (through turbulent heat transfer). The pressure is assumed to vary only in the axial direction. If the interfacial exchange processes (mixing) and the losses are modeled sufficiently well, the CFA code can provide accurate estimates for the behavior of variable area, mixer-ejector nozzle flows. Further these estimates can be obtained with relatively short computation times (a few minutes). This rapid calculation ability allows the code to be imbedded in a multi-parameter optimization scheme.

Various sub-component models which have been incorporated into the CFA code are described below:

3.1.1 Primary Nozzle and Secondary Inlet Losses

Losses in the primary nozzle and in the secondary inlet are calculated using correlations recently obtained from Pratt and Whitney. Correlation constants can be changed to reflect various testing configurations.

3.1.2 Pressure Matching Model

In order to account for mismatched pressures at the mixer exit, a control volume is placed at the front end of the CFA code. At the exit of the control volume, the pressures are matched. The amount of momentum and energy transferred across the pressure matching region is assumed to be the same as if the two streams were matched throughout. Therefore, the pressure matching region can be assumed to be the superposition of a control volume of negligible length with no momentum and energy transfer and the CFA code starting at the mixing plane.

3.1.3 Wall Shear Stress

Correlations were used that modeled both laminar and turbulent boundary layers. The turbulent wall friction coefficient was found using a correlation developed by White and Christophe (1972).

3.1.4 Interstream Shear Stress

An analysis by Goertler was used to predict the interstream shear stress. From this analysis, both the velocity profile and the interstream shear stress can be expressed in terms of the free stream values and a shear layer growth rate parameter. The shear layer growth rate is assumed to be a function of the convective Mach number (M_c), the density ratio (s), and the velocity ratio (r).

The incompressible pitot thickness growth rate is first calculated using a relation given by Brown and Roshko:

$$\delta'_{pitot,inc} = 0.14 \frac{(1-r)(1+\sqrt{s})}{(1+r\sqrt{s})}$$

The ratio of the compressible pitot thickness to the incompressible pitot thickness is then correlated against the convective Mach number using empirical data from Papamoschou and Roshko. The compressible pitot thickness is roughly equal to the incompressible pitot thickness for $M_c < 0.25$, then drops off linearly to one-fifth of the incompressible value at $M_c = 0.5$. Corrections for total temperature variations are made based on the Munk and Prim Approximate Substitution Principle. The constants in these expressions were determined by comparing predicted mass flow rates to experimental data from the Boeing Single Lobe experiments.

3.1.5 Interstream Thermal Conduction

The amount of thermal energy transferred between the two streams due to temperature gradients is given by Fourier's equation.

$$\dot{q} = k \frac{dT}{dy}$$

The thermal conductivity (k) is calculated using correlations for air. The thermal gradient is assumed to be such that the energy transferred per unit length is a function of the axial direction only.

3.1.6 Evolution of Interfacial Length

For mixers with little streamwise vorticity, the perimeter between the two streams is approximated using geometrical relations. Initially, the interface length is equal to the perimeter of the mixer lobes. As the shear layer grows, the perimeter becomes the same as for a planar shear layer.

For flows with significant streamwise vorticity, the interface length increases due to the winding of the shear layer. A high-fidelity mixing model based on potential flow theory has been developed to capture the evolution of the mixing interface. This mixing model will be described in greater detail in the Ph. D. Thesis of Mr. David Tew which is expected to be completed during the summer of 1996. The code is currently being validated and it will be incorporated into the CFA code in the future.

3.1.7 Compound Shocks

An additional feature of the CFA code is the ability to place compound shocks. The compound shock is modeled as a control volume. The pressure in the two streams are equal but change across the shock. The two stream areas are also discontinuous across the shock. In order to write the momentum equation, it is assumed the pressure varies linearly across the shock. For two identical streams, the control volume reduces to the normal shock equations. Compound shocks may be useful for explaining the behavior of "mode shifts," which are accompanied by rapid changes in static pressure.

3.2 Validation and Refinement of CFA Sub-component Models

A preliminary version of the MIT noise suppressor system model has been transferred to researchers at Pratt and Whitney and Boeing. It is expected that the code will be transferred to researchers at NASA Lewis Research Center and General Electric in the near future.

Initial validation and refinement of the subcomponent models in the CFA code is currently underway. Using the CFA code, comparisons between predicted mass flow rates and measured flow rates for the Boeing Single Lobe experiments were made. The predicted mass flows agreed to within 15% over the complete range of NPR from 1.5 to 5.5. Near the matched condition (NPR=3) the predicted mass flows were accurate to within 5%. Since these comparisons involve Limited Exclusive Rights Data (LERD), they are not included with this report. Initial comparisons have also been made with HSRP GEN 1.5 data, and we are currently working with the Nozzle ITD Team to integrate empirical best estimates of component losses, MIT mixer lobe loss models and inlet performance models into the CFA code, so that more accurate comparisons can be made.

4.0 Plans for Next Year

4.1 Continued validation and refinement of the CFA code

In the future we will continue to work with the Nozzle ITD Team to perform iterative development, integration, and validation of sub-component models. This work will include:

- 1) Back-to-back comparison with the Boeing CFA model,
- 2) Back-to-back comparison with General Electric (Kuchar) 'best-achievable-performance' estimates
- 3) Integration of high-fidelity, vortex dynamics mixing model into the noise suppressor system model.
- 4) Validation of MIT vortex dynamics mixing model through comparison with experimental data obtained from MIT/UTRC shear layer experiments and Boeing LSAF laser velocimetry data.
- 5) Incorporation of simplified first-order analyses for acoustic radiation (internal and external) into the mixer-ejector system model.
- 6) Integration of an analytical model for nozzle weight (provided by ITD Team) into the mixer-ejector system model

4.2 Optimization of Mixer-Ejector Noise Suppressor Designs

After completing the development of a noise suppressor system design tool which links details of the ejector geometry and flow conditions to thrust coefficient, mixing performance, radiated noise, and weight, the tool may be imbedded in an optimization scheme and used to guide the design of practical devices.

The first step in optimization is to form a cost function, a measure to compare designs. The cost function should account for such figures of merit as the noise, thrust, weight, and drag of the mixer ejector system. There are two ways to include a figure of merit in a cost function. One is to assign a weighting to each figure of merit. This is what is done when designers express a desired noise reduction in terms of dB per % drop in gross thrust coefficient (cfg). The other way is to form a constraint. This is a common way of accounting for weight and drag considerations. A Lagrangian optimization problem can be formed by combining these two methods into a single cost function.

Once a Lagrangian is formed, the optimization can be carried out using an appropriate gradient method. The necessary derivatives will be numerically determined using the CFA code. In addition to the optimum design and performance, the sensitivities of the performance to the constraints is a natural byproduct of a Lagrangian optimization problem. By varying the cost

function, the optimal performance can be examined as part of the overall vehicle. Finally, the sensitivity of the optimization to key models in the simulation can be examined.

5.0 Summary

Currently, the CFA framework is complete and is being compared to experimental data. These comparisons will be used to synthesize more accurate models where necessary. Once the evaluation and improvement of the separate models is completed, the CFA will be embedded into an optimization routine. The system will be optimized with respect to noise, thrust, weight, and drag. The goal is to determine the optimal performance given a set of operating conditions.

6.0 Personnel

The principal investigator for this work will be Dr. Ian A. Waitz, Assistant Professor of Aeronautics and Astronautics. A resume is attached in Appendix A. Dr. Edward M. Greitzer, Professor of Aeronautics and Astronautics, and Dr. Choon S. Tan, Principal Research Engineer, will be co-investigators on the project. Funding to support one graduate research assistant is requested.

6.0 Estimated Budget

Funding of \$116,906 is requested. This includes \$10,500 for experimental materials and services. This money will be used for experiments at UTRC and in the MIT Shock Tube Facility which are dedicated to validation of the noise suppressor system model. The estimated budget is attached in Appendix B.

Appendix A

Resume of Principal Investigator

IAN A. WAITZ

Assistant Professor of Aeronautics and Astronautics
Massachusetts Institute of Technology

Director, MIT Aero-Environmental Research Laboratory
Member, MIT Gas Turbine Laboratory
Building 31, Room 268
77 Massachusetts Avenue, Cambridge, Massachusetts 02139

Born January 25, 1964, Ann Arbor, Michigan
U. S. Citizen

Education:

Ph. D.	1991	Aeronautics, California Institute of Technology
M. S.	1988	Aeronautics, George Washington University
B. S.	1986	Aerospace Engineering, The Pennsylvania State University

Teaching Experience:

Environmental Aerospace Engineering. Developed to address the growing impact of environmental concerns on aerospace systems. Concentration on aircraft emissions and noise is set within a broad contextual backdrop, including discussions of ethics, regulatory measures, environmental assessment, global change, economics, urban planning, and policy.

Aircraft Propulsion and Gas Turbines Graduate level course devoted to performance and characteristics of aircraft engines and industrial gas turbines as determined by the thermodynamic and fluid mechanic behavior of components: inlets, compressors, combustors, turbines and nozzles.

Internal Flows in Turbomachines. Advanced graduate level course covering concepts of rotational flows, inherent unsteadiness of turbomachines, boundary layers, and wakes and losses in turbomachines.

Experimental Projects I and II. Selection and detailed planning of an individual research project during the first semester, is followed by construction and experimentation during the second semester. Formal written and oral presentations are made by each of the students.

Unified Engineering. Sophomore level undergraduate course presents the fundamentals of solid mechanics, fluid mechanics, dynamics, thermodynamics and propulsion, and forms the foundation for all other courses taught by the department. The course is the equivalent of four semester-long courses, and is cooperatively taught over the period of a year by several faculty.

Research:

Lobed mixers: Experimental and computational investigations are proceeding to characterize mixing and losses of lobed mixer geometries designed for introduction of strong axial vorticity for applications on gas turbine engines.

Ejectors for jet noise reduction: Advanced mixer/ejector devices are being studied both computationally and experimentally to provide insight into basic fluid mechanics and acoustics in an effort to develop design procedures for these devices.

Streamwise vorticity in combustor flows: Experiments are being carried out to measure the effects of strong streamwise vorticity on flame propagation, flame stability, and combustion efficiency for applications to emissions reduction, and thrust augmentor performance enhancement.

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Reduction of turbomachinery fan noise: Numerical simulations and experiments are being carried out to investigate the impact of various blade wake management strategies on rotor-stator interaction tone noise.

Chemical Processes in the Turbine and Exhaust Nozzle: To aid in assessing the atmospheric effects of current and future aircraft, a numerical investigation is being conducted of the chemistry of the primary pollutant species, short-lived radicals, and aerosols, in the non-uniform flow downstream of the combustor, in the turbine and exhaust nozzle.

Micro-Engines: Conducting experimental and numerical research in micro-scale combustion systems to support the development of a 1mm x 1mm inlet area micro-gas turbine generator using MEMS technology.

Vortical structures in compressor endwall flowfields: Experimental and computational investigations of blade tip clearance flows are directed towards elucidating basic fluid mechanics and impact on performance and stability.

Mutagenicity of Gas Turbine Emissions: Conducted sampling and analysis of gas turbine exhaust emissions in conjunction with the MIT Center for Environmental Health Sciences to determine human health impacts.

Hypersonic mixing and combustion: Conducted hydrogen-air combustion studies in a free-piston shock tube facility at Mach 16 flight conditions. (with Caltech Profs. F. E. Marble and E. E. Zukoski)

Doctoral dissertation: "An Investigation of Contoured Wall Injectors for Hypervelocity Mixing Augmentation", with Drs. E. E. Zukoski, F. E. Marble and T. Kubota at the California Institute of Technology, Pasadena, California.

The goal of the research was to enhance the mixing-rate dominated combustion process in the supersonic combustion ramjet engines currently envisioned for applications on hypersonic vehicles. Experimental work in the NASA Langley High Reynolds Number Mach 6 Wind-Tunnel was complemented by a significant computational effort.

Master's thesis: "An Experimental Investigation of Transition Due to Sound and Roughness on a Disk Rotating in Still Air", with S. Wilkinson and D. B. Bushnell at the Joint Institute for the Advancement of Flight Sciences, George Washington University at NASA Langley Research Center, Hampton, Virginia.

Addressed fundamental issues of receptivity and transition in three-dimensional boundary layers by studying the combined effects of roughness and acoustic forcing on the transitional, cross-flow boundary layer generated on a flat disk rotating in quiescent air.

Undergraduate thesis: "The Effects of Wing-Fuselage Integration Geometries on Total Sailplane Drag", with Dr. M. Maughmer at The Pennsylvania State University, University Park, Pennsylvania.

Consulting:

9/91 - 11/92	California Institute of Technology, Pasadena, California Supersonic combustion, testing and analysis
3/93 - 1/95	PRC Inc., Mt. Laurel, New Jersey Internal flow design and analysis
7/94 - 3/95	Thermo Energy Systems Corporation, Waltham, Massachusetts Analysis of novel fluid-dynamic power generation scheme

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11/94 - 3/95	Cummins Engine Company, Inc., Columbus, Indiana Analysis of gas-turbine technology trends for power generation markets
3/95 - 2/96	Telectro-Mek, Inc., Fort Wayne, Indiana Development of thrust measuring systems for aircraft
3/95 - 1/96	Visidyne, Inc., Burlington, Massachusetts Analysis of flow diagnostic techniques
1/96 - present	General Electric, Aircraft Engines Group Gas turbine test facility evaluation
12/95 - present	Allison Advanced Development Company Conducting wind-tunnel experiments
2/96 - present	United Technologies Pratt and Whitney Gas turbine combustion
2/96-3/96	Rasor Associates, Inc. Evaluation of combustion process

Publications:

"Experimental Investigation of Wing/Fuselage Integration Geometries",
M. Maughmer, D. Hallman, R. Ruszkowski, G. Chappel, and I. Waitz, *Journal of Aircraft*, Vol. 26, no. 6, August, 1989.

"Rotating Disk Transition Due to Isolated Roughness with Intense Acoustic Irradiation",
I. Waitz and S. Wilkinson, AIAA 88-3761, presented at the First National Fluid Dynamics Congress, Cincinnati, Ohio, July 24-28, 1988.

"Shock Enhancement and Control of Hypersonic Mixing and Combustion",
F. Marble, E. Zukoski, J. Jacobs, G. Hendricks, and I. Waitz, AIAA 90-1981, presented at the AIAA/SAE/ASME/ASME 26th Joint Propulsion Conference, Orlando, Florida, July 16-18, 1990.

"Investigation of a Contoured Wall Injector for Hypervelocity Mixing Augmentation",
I. Waitz, F. Marble, and E. Zukoski, *AIAA Journal*, Vol. 31, no. 6, June 1993.

"Planar Rayleigh Scattering Results in Helium-Air Mixing Experiments in a Mach 6 Wind Tunnel," B. Shirinzadeh, I. A. Waitz, J. Balla, M. E. Hillard, J. B. Anders, and R. J. Exton
Applied Optics, Vol. 31, No. 30, October, 1992.

"A Systematic Experimental and Computational Investigation of a Class of Contoured Wall Fuel Injectors," I. Waitz, F. Marble, and E. Zukoski, AIAA 92-0625 presented at the AIAA 30th Aerospace Sciences Meeting, Reno, Nevada, January 6-9, 1992.

"Vorticity Generation by Contoured Wall Injectors", I. Waitz, F. Marble, and E. Zukoski, presented at the AIAA/SAE/ASME 28th Joint Propulsion Meeting, Nashville, Tennessee, July 6-8, 1992.

"Vortices in Aero-Propulsion Systems", I. Waitz, E. Greitzer, and C. Tan, in *Fluid Vortices*, ed. S. Green, Kluwer Academic Publishing, 1994.

"A Computational Study of Viscous Effects on Lobed Mixer Flow Features and Performance,"
M. N. O'Sullivan, I. A. Waitz, E. M. Greitzer, C. S. Tan, and W. N. Dawes, *AIAA Journal of Propulsion and Power*, Volume 12, Number 2, March-April 1996.

"Enhanced Mixing in Gas Turbine Propulsion Systems," I. A. Waitz, T. G. Tillman, D. C. McCormick, *Global Gas Turbine News*, International Gas Turbine Institute, August 1993.

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"Streamwise Vorticity Enhanced Mixing," I. A. Waitz, J. K. Elliot, A. K. S. Fung, J. M. Kerwin, J. K. Krasnodebski, M. N. O'Sullivan, Y. J. Qiu, D. E. Tew, E. M. Greitzer, F. E. Marble, C. S. Tan, and T. G. Tillman, working paper.

"Preliminary Assessment of Wake Management Strategies for Reduction of Turbomachinery Fan Noise," I. A. Waitz, J. M. Brookfield, J. Sell, and B. J. Hayden, CEAS/AIAA 95-102, presented at the First Joint CEAS/AIAA Aeroacoustics Conference, Munich, Germany, June 12-15, 1995.

"Streamwise Vorticity Enhanced Mixing in a Reacting Shear Layer," D. S. Underwood, and I. A. Waitz, AIAA 95-2471, presented at the 31st AIAA/ASME/SAE/ASEE Joint Propulsion Conference, San Diego, CA, July 10-12, 1995.

"The Role of Streamwise Vorticity in Compressible Mixing Downstream of Lobed Mixers," D. Tew, I. Waitz, J. Hermanson, and E. Greitzer, AIAA 95-2746, presented at the 31st AIAA/ASME/SAE/ASEE Joint Propulsion Conference, San Diego, CA, July 10-12, 1995.

"Integrated Teaching of Experimental and Communication Skills to Undergraduate Aerospace Engineering Students," I. A. Waitz and E. C. Barrett, to be presented at the 1996 ASEE Annual Conference and Exposition, June 1996.